Magnetic Properties of Fe/V(001) Superlattices Studied by Resonant Scattering of Polarized X-Rays

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The magnetic properties of artificially structured devices can be tailored to specific needs using appropriate elements, growth modes or periodic structures. Metallic multilayers, featuring oscillating magnetic coupling and giant magnetoresistance effects, are preeminent among such devices. Fe/V superlattices are a good example of how a multilayer device can present a whole variety of magnetic behavior, depending on the layer thicknesses t_{Fe} and t_V, and on the crystal orientation [1]. Until recently, the magnetic properties of V in these layers have been subject to controversy, since it is difficult to investigate the weak magnetism of V in a superstructure containing a large amount of Fe. The only studies of the V magnetism in multilayers have been performed by circular dichroism at the 2p absorption edge [2], detecting the sample drain current or, equivalently, the total electron yield (TEY). Circular dichroism in x-ray absorption spectroscopy (XAS) is a powerful technique because of its element selectivity and the access it gives to a quantitative evaluation of magnetic moments via the application of sum rules, but the TEY detection mode has several drawbacks that have been discussed in the past [3]. We have adopted a different experimental approach, based on x-ray resonant magnetic scattering (XRMS), which takes full advantage of all aspects of dichroism in x-ray absorption, along with some additional technical and conceptual points of interest. As in XAS, we use photons tuned to core excitation resonances, obtaining element selectivity, and we can excite the 2p $\rightarrow$ 3d dipole transitions that directly probe the 3d magnetic orbitals. In addition, soft x-ray wavelengths match the typical spacings of metallic multilayers, so Bragg diffraction experiments under resonant conditions may be performed. Another relevant aspect of XRMS, when dealing with magnetic multilayers, is that it is a photon-in / photon-out experiment which means that the presence of applied magnetic fields does not affect the measurements. Moreover the probing depth is only limited by the photon path within the sample and no saturation effects need to be accounted for. The large probing depth is very important if we wish to extract bulk properties from capped multilayer samples (i.e., not those just related to the topmost layers).

The superlattices were epitaxially grown by sputter deposition of the metallic layers on MgO(001) single-crystal substrates. Their final structure is (Fe 5 ML / V n ML $)_m$, where ML means monolayers, with (n = 1, m = 80), (n = 2, m = 60), and (n = 5, m = 40). Their structural properties have been described previously [1]. The easy axes of magnetization are always along the [110] axes of the substrate, i.e. [100] in-plane directions of the superlattice.
XRMS measurements were performed at the Fe and V 2p edges on beamline 6.3.2 at ALS [4] using elliptically polarized light (40 % circular polarization rate). The external magnetic field, applied along an easy axis, in the sample surface and in the scattering plane, was reversed after each energy scan. We also measured the absorption spectra and circular dichroism under the same experimental conditions by the drain current detection method. As implicitly suggested

above, the probing depth is small (about 15 Å in Fe): this implies that we are only measuring a few layers of our sample. Moreover, only the outermost layers are probed which are more likely to be affected by inhomogeneities, contamination or by the presence of the capping layer (Pd, in our case).

We needed the absorption lineshapes to build up the dielectric tensor for Fe and V employed in the analysis of XRMS data, leaving as a free parameter a multiplication factor on the magnetization dependent part of the optical constants. Using the computational method described in a previous paper [5], we were thus able to fit the magnetization dependent part of the optical constants to the ensemble of the energy and angle dependent scattering curves, including resonant Bragg diffraction spectra.

All resonant spectra showed magnetization dependence. Fig. 1, for instance, shows the energy dependent reflectivity curves for the n=1 sample: the left panels refer to the V and Fe 2p edges, measured at θ=10 degrees. Full and dashed lines are the sum and the difference of reflectivity curves obtained for opposite magnetizations. In the right panel, the corresponding asymmetry ratios are presented. We have drawn them on different energy scales so as to give a visual match of the 2p spin-orbit separations for Fe and V.

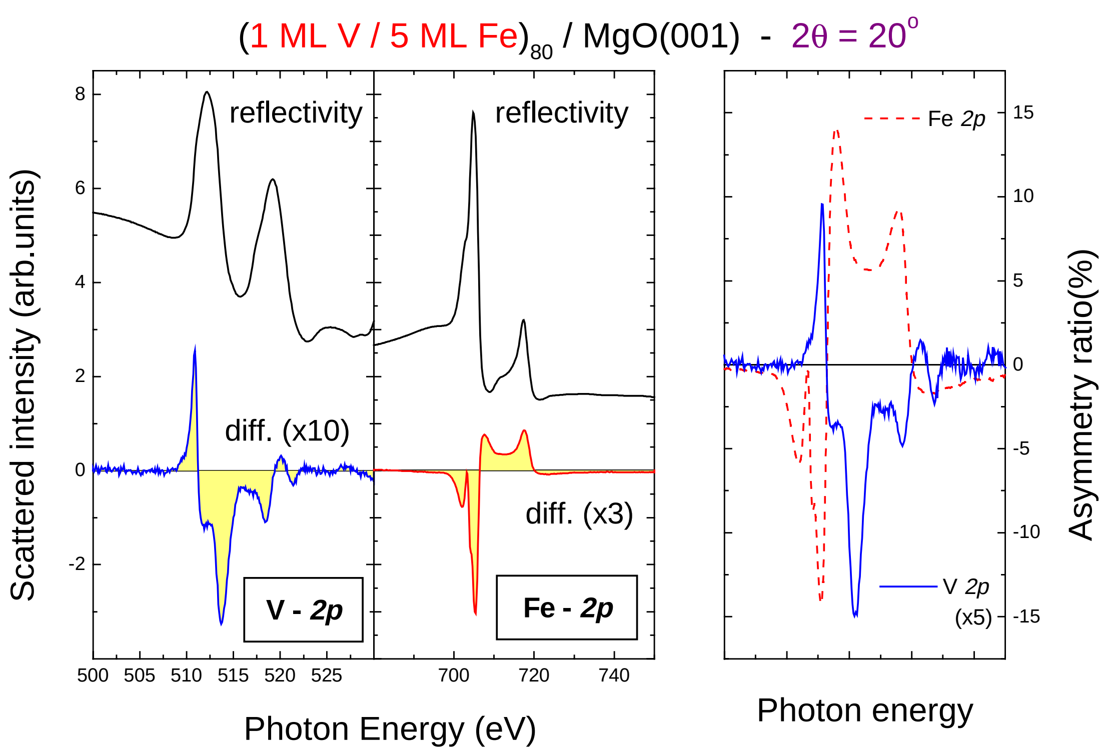

Figure 1. Resonant reflectivity at the V and Fe 2p edges for the n=1 sample and corresponding magnetic signals. Right panel : asymmetry ratio curves on an arbitrary energy scale in order to visually match the spin-orbit splitting of the 2p core hole for Fe and V.

Fitting the XRMS spectra at the Fe 2p edge gave optical constants such that the dichroism curves in absorption did not deviate appreciably from that of a bulk Fe reference. Applying sum rules, we obtained values of the magnetic moment per Fe atom between 2.1 and 2.3 μ_B, depending on

choices made in the data reduction. We conclude that for these multilayers there is no measurable change in the Fe average magnetic moment as a function of V thickness. This also implies a ferromagnetic alignment of all the Fe layers in the superstructure.
Fig. 2 compares experimental asymmetry ratio curves at the V 2p edges with best fit calculations. Only one scattering angle per sample is shown, but the fitting procedure included at least five different angles per sample. For a more quantitative analysis, we have applied sum rules to the V 2p absorption spectra corresponding to the optical constants derived from the fit.

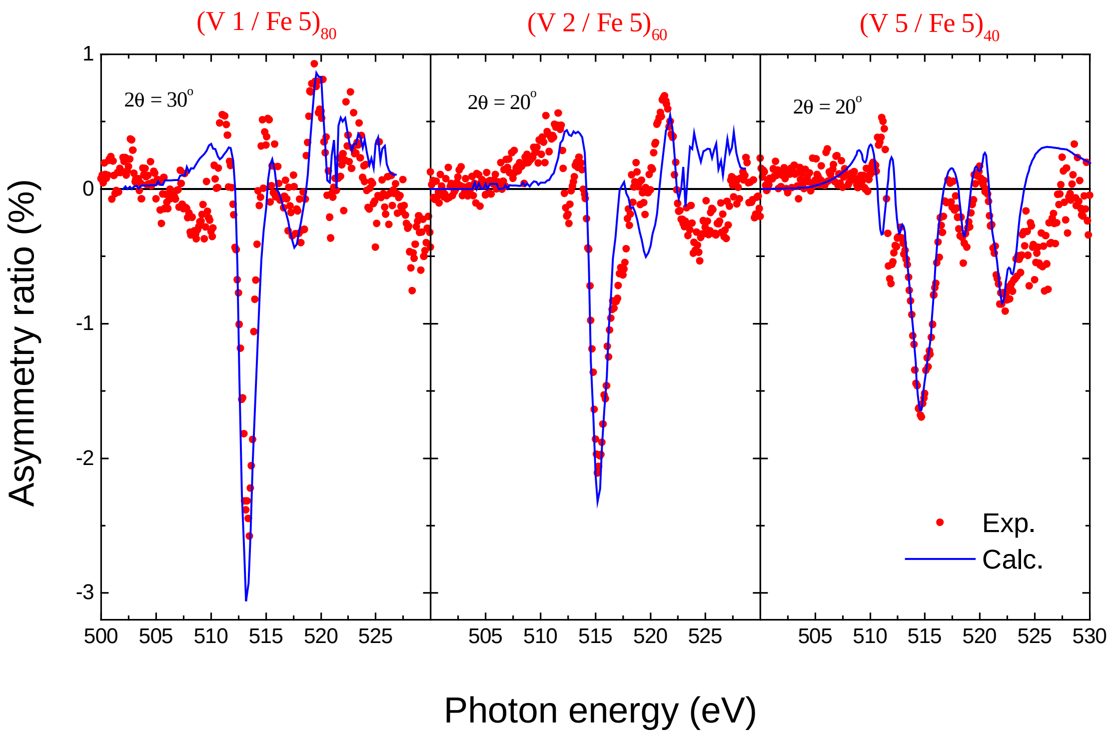

Figure 2. Experimental asymmetry ratio curves at the V 2p edges for n=1, 2 and 5. Lines are best fits obtained varying the magnetisation dependent part of the optical constants.

The main qualitative and quantitative results of our XRMS experiment on (Fe 5 / V n)$_m$ (001) superlattices can be summarized as follows:

i) the magnetic moment of iron does not change with respect to its bulk value, regardless of the V thickness, at least to within the sensitivity of the method;
ii) the coupling between Fe layers is ferromagnetic for V spacers up to 5 ML;
iii) for all the samples under study, the V 3d band carries a magnetic moment and its coupling to Fe is always antiferromagnetic;
iv) for n=1, the orbital moment is of the order of -0.08 μ_B and the spin moment 0.37 μ_B, giving an average total magnetic moment of 0.66 μ_B per vanadium atom;
v) this value reduces to 0.40 μ_B and 0.26 μ_B for n=2 and n=5, respectively.

In conclusion, XRMS has a large probing depth, it is not affected by applied magnetic fields, and it provides spectroscopic as well as structural information. These characteristics make it an interesting complement to dichroism in absorption. We have shown that sum rules developed for x-ray absorption may also be applied to resonant scattering data to extract quantitative information. Moreover, XRMS may be used to distinguish magnetic arrangements with different magnetization profiles, even when they have the same average properties. Together with its intrinsic element selectivity, this opens the way to interesting future applications in the field of magnetic multilayers.

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